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ESTABLISHING AND MAINTAINING A COLOR TEMPERATURE SCALE

W. E. FORSYTHE AND E. Q. ADAMS

Received December 21, 1942; published May 21, 1943

INTRODUCTION

There are many methods that can be used to bring an incandescent lamp or other source of continuous radiation to a pre-determined radiating condition, and one of these is to bring it to the corresponding color temperature. The color temperature of a radiator is defined as the temperature at which it is necessary to operate a blackbody, the standard radiator, so that the emitted light of the blackbody will match in color that of the source studied. Such color matches can be very accurately made by eye observation, using the ordinary photometer equipped with a contrast photometer cube. To make a color match involves a double setting. First a setting must be made for the condition of equal illumination on the two sides of the photometer screen, that is a brightness match, by moving one of the sources of light or the photometer head. When this has been done, if the two sources are not giving light of the same color, the trapezoid of the contrast photometer that is illuminated by the source of lower color temperature, say the comparison lamp, will appear pink as compared to the other trapezoid which will appear blue. The temperature of the comparison lamp is then raised by increasing its applied voltage until the two trapezoids appear the same in color, keeping of course an intensity match by moving either the comparison lamp or the photometer head. To avoid errors that might be introduced by the photometer, for this as for all photometric measurements, the method of substitution should be used. Thus the light from both the standard and the unknown source should be color-matched in turn with that of a comparison lamp.

It should be pointed out here that when two sources are set at the same color temperature, they may or may not be giving the same amount of light. Although the higher-wattage lamps are in general operated at the higher temperature, a 100 candlepower lamp may have the same color temperature as a lamp with a light output of 1000 candles. This will be again brought out when color-temperature-altering filters are discussed.

Since it is a difficult and time-consuming job to operate a blackbody at a number of definite temperatures, the color-temperature scale is generally maintained by the use of tungsten lamps calibrated for a range of color temperatures in terms of their applied voltages.

Some years ago it was decided to establish a color-temperature scale at the

laboratory at Nela Park for use in studying the radiating characteristics of carbon and tungsten, and of carbon, tungsten, and other incandescent lamps. When this work was started, the incandescent lamps used covered a range of color temperatures from about 2100 to 2800°K. At that time a temperature of 2800°K was higher than a color-temperature scale had been established, and it was higher than it was generally thought possible to operate a blackbody furnace.

The Blackbody. One way of defining the blackbody is: It is a body that will absorb all the radiation that falls upon it, neither reflecting nor transmitting any of the incident radiation. Radiation has many meanings, but here that type of radiation that originates from a solid material, due to its temperature alone, is meant. Stated technically, it is the type of radiation that is transmitted by electromagnetic waves and is called radiant energy.

Getting back to the blackbody discussion: from the above definition, and from some very plausible assumptions, it can be shown that for equal area and time, the blackbody will radiate more energy than any other temperature radiator at the same temperature. Stated another way, the blackbody will radiate more energy than any other body at the same temperature when radiation is due to temperature alone.

Radiation Laws of the Blackbody. The outstanding advantage of the blackbody as a radiator is that it has been shown by both theory and experiment that the radiation given by it, when it is at any temperature, depends only upon this temperature and certain constants, and finally the relation between the energy radiated and the temperature has been established which means that if the temperature of the blackbody is known, its radiating characteristics are completely determined. The first of these relations shows that the total radiation from a blackbody at any temperature varies as the fourth power of the absolute temperature, i.e.,

$$\Phi = AW = A\sigma T^4 \tag{1}$$

where Φ is the total energy radiated per unit time, T the absolute temperature, A, the area and σ a constant [about 5.7×10^{-12} watts/(cm^2 deg^4)] that had to be determined experimentally. This equation was derived before anyone had found out how to construct and operate a blackbody.

It required three attempts to derive the relation between the temperature and the radiation intensity for different wavelength intervals, that is, the mathematical expression representing the law that shows how the radiation intensity from a blackbody is distributed in the spectrum for any temperature of the blackbody. Wien's first attempt produced his well-known displacement law. This was developed using thermodynamic reasoning. With radiation as a working substance in a Carnot cycle, Wien showed that

$$J_\lambda = Ac_1\lambda^{-5}F(\lambda T) \tag{2}$$

where J_λ is the spectral radiant intensity for wavelength λ. This was an outstanding advancement because it showed that the distribution of radiant in-

tensity in the spectrum of the blackbody depends only upon the temperature and the wavelength, and as far as the blackbody is concerned, only upon its temperature. This development told nothing about the kind of function represented by $F(\lambda T)$. So far as this law is concerned, the spectral intensity might have any number of maxima. However, there are two corollaries of this displacement law that give some interesting information. These corollaries are derived by setting up the conditions for the single maximum, with respect to wavelength, that the radiation from a blackbody is known to have and solving the resulting equation. These corollaries* are

$$\lambda_m T = b_1 \tag{3}$$

$$J_m/(AT^5) = b_2 \tag{4}$$

Equation (3) gives the relation between the wavelength and the temperature for the maximum intensity for any temperature (b_1 is a constant) and (4) shows the value of the maximum intensity for any temperature (b_2 is a constant). Wien then attempted to find the form of $F(\lambda T)$ by thermodynamic and electrodynamic reasoning and obtained the following

$$J_\lambda = Ac_1\lambda^{-5}\mathbf{e}^{-\frac{c_1}{\lambda T}} \tag{5}$$

This equation did not fit the experimental data for high temperature and long wavelength, but is in excellent agreement with experiments for small values of the product λT. For (λT) less than 3,000 microns °K, the agreement with experiment is better than one percent. Meanwhile, Raleigh and Jeans using thermodynamic and electrodynamic reasoning derived the following equation

$$J_\lambda = Ac'\lambda^{-4}T \tag{6}$$

which should hold if radiation is continuous. It is known that this law cannot hold since the radiation from a blackbody has a maximum for some wavelength and this equation shows no maximum. Thus neither the Wien nor the Raleigh-Jeans law represents the facts for all temperatures and all wavelengths.

Planck then attacked the problems and to obtain a solution in keeping with the measured radiation fron the experimental blackbody was obliged to introduce the new and revolutionary idea that radiation was not a continuum but was made up of quanta. This quantum energy has a peculiar magnitude, i.e., $q = ch/\lambda$ where h is a constant, c the velocity of light, and λ the wavelength. Thus the quantum of energy is different for different wavelengths. Planck's idea was that radiation is both emitted and absorbed as quanta. Thus by assuming that radiant energy is made up of some sort of particles, Planck showed that the radiation from a blackbody at any temperature is distributed among the different wavelengths (colors in the visible spectrum) according to a definite law, and that the only factors that enter into this law besides constants are the wavelength and the temperature.

This law, called the Planck Radiation Law, cannot be given by as simple an

* The first of these corollaries is often erroneously given as Wien's displacement law.

equation as the one giving the total radiation, but none the less it represents very exactly the experimental facts. It is

$$J_\lambda = \frac{Ac_1\lambda^{-5}}{e^{\frac{c_2}{\lambda T}} - 1} \tag{7}$$

where J_λ is the spectral radiant intensity at wavelength λ, and c_1 and c_2 are constants that had to be determined experimentally. A is the area of the blackbody, e the base of natural logarithms (i.e., 2.718+), and T the absolute temperature.

Constructing and Operating a Blackbody. For the visible spectrum (eye observations), it is easy to pick bodies that absorb practically all the radiation that falls upon them and reflect almost none of the incident radiation—that is bodies that are black—such as black felt, black velvet, blackboards, carbon

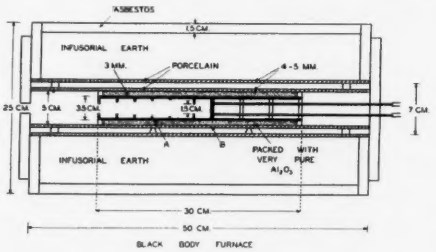

FIG. 1. Diagram of blackbody furnace. Tube A and Tube B are wound with the platinum ribbon heating element; Tube A with the windings uniform, and Tube B with the windings spaced closer at the ends and separated in the center to help correct for end cooling. The space between Tube A and Tube B is filled with pure aluminum oxide.

black, etc. Bodies that appear black to the eye, i.e., that are approximate blackbodies within the visible spectrum, may or may not be blackbodies for the wavelength regions outside of the visible spectrum.

It can be shown that any completely enclosed cavity, with walls of any opaque material (with finite emissivity for all wavelengths), contains, if the walls are at a uniform temperature, blackbody radiation of the same temperature as that of the walls. This means that the radiation within such a cavity is fully defined as to its intensity and distribution among the different wavelengths by equations (1), (3), (4), and (7).

If a small opening, i.e., small with respect to the area of the cavity walls, is made into this cavity, the radiation escaping from this opening will be, within a small fraction of a percent, the same as that within the cavity, that is it will be blackbody radiation that has the same temperature as the walls of the cavity. (The radiation emerging from the small hole is the more nearly equal to the blackbody radiation within the cavity, the relatively smaller the hole is.) Thus the production of a cavity with a small opening and with walls that can be brought to a uniform temperature gives a method of physically realizing a blackbody for experimental purposes.

Many different types of cavity blackbodies have been developed and Figures 1, 2, 3, 4 and 5 show some of the types that have been used (*1*) in experimental work. It is to be noted that each of these types has a small cavity that can be heated to a uniform temperature.

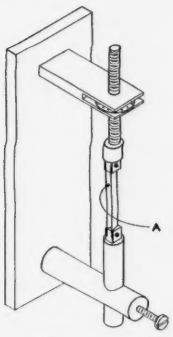

FIG. 2

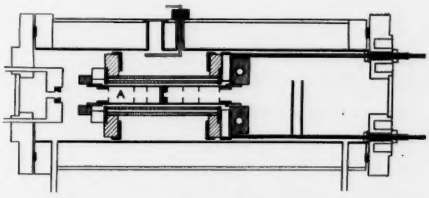

FIG. 3

FIG. 2. C. E. Mendenhall's open-wedge blackbody
FIG. 3. Diagrammatic sketch of carbon-tube blackbody furnace

FIG. 4

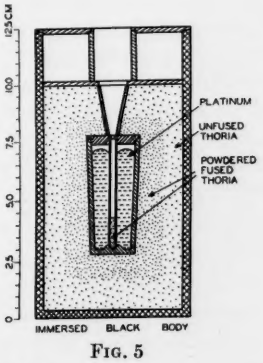

FIG. 5

FIG. 4. A. G. Worthing's tungsten-tube blackbody furnace
FIG. 5. Diagram of special blackbody furnace used at National Bureau of Standards for establishing the Waidner and Burgess standard of light intensity.

Blackbody furnaces of the cavity type have been constructed in different laboratories in many parts of the world, and measurements made of the radiation output that check well within the accuracy of the measurements.

The Value of the Blackbody. As has already been pointed out, the blackbody owes its importance to two facts—it is comparatively easy to construct and operate a cavity blackbody, and the characteristic of its radiation is completely determined by its temperature. This is true of no other radiator. Many

other radiators, e.g., tungsten filaments, are very constant and very reproducible in their radiation characteristics, but other factors than the temperature are necessary to describe their radiation. The radiation of any radiator other than the blackbody depends upon its surface conditions. For example, some care must be exercised with a tungsten filament to bring the surface to a condition where it will give, within a small percentage, the reproducible radiation characteristic of tungsten. But to have a blackbody emit its characteristic radiation, it is only necessary to construct one of the cavity type of almost any material, observing certain definite precautions in its construction, and then to bring the walls of the cavity to a definite temperature.

The Blackbody as a Standard of Intensity and of Color. The blackbody has two principal uses, viz., as a standard of intensity, and as a standard of color of integral light. It is used as a standard of intensity against which to calibrate radiation and optical pyrometers. For this purpose, the blackbody is generally held at some standard temperature, such as the melting point of gold (1336°K) or of palladium (1827°K). It is also used as a standard of light intensity, again at a standard temperature, the freezing point of platinum, 2046°K. As a standard of color, the blackbody is used to give the integral color of the light from various sources.

Establishing a High Temperature Scale. As the first step towards the establishment of a color-temperature scale, it was thought necessary to establish a high temperature scale for the laboratory, in terms of a calibrated disappearing-filament optical pyrometer, based on the brightness of a blackbody at the temperature of two standard melting points (*2*)—gold at 1336°K and palladium at 1823°K.* To establish these standards of brightness, a number of electrically heated blackbody furnaces, with platinum as the heating element, were constructed along the general lines of the one shown by cross section in Fig. 1. Then these blackbody furnaces were brought to one or the other of these standard temperatures by melting samples of either very pure gold or very pure palladium in the furnace and holding the furnace at this temperature as will be described later. In the construction and operation of the blackbodies, and in the construction, calibration, and operation of the disappearing-filament optical pyrometer, several difficulties were encountered that required some special investigation before the final task could be completed.

If platinum ribbon is used as the heating element of a blackbody furnace, some care must be exercised when the blackbody is operated at the temperature of melting palladium, since the melting point of platinum is only about 220°C higher than that of palladium, which does not give much margin in the operating temperature between the melting point of the platinum heating element and the temperature of the furnace. It had long been known that such a furnace had to be well made and that two heater tubes—one outside the other—had to be used if the furnace were to be operated for any length of time for a temperature so near the melting point of the platinum heater element. It was found that if

* 1910 value of Day and Sosman. See pp. 8 and 9.

the space between the two heater tubes was tightly packed with very pure aluminum oxide, the furnace would both operate at a more uniform temperature and have a longer life.

One point of the calibration of a disappearing-filament optical pyrometer, which is essentially a telescope with the pyrometer filament at the focus of the eyepiece, is made by sighting it on a blackbody at a definite temperature and balancing the brightness of the filament with that of a blackbody by varying the current through the pyrometer filament. From the blackbody operated at the two standard temperatures, two points of such calibrations are obtained. Other points of the calibration of the pyrometer can be obtained by the use of rotating sectors (*3*) between the blackbody furnace held at a definite temperature (palladium point) and the objective lenses of the pyrometer. Thus supposing that one uses a sector that transmits one-half of the radiation from the furnace at temperature T, then the intensity of this transmitted radiation corresponds to a certain temperature T_x, which can be calculated from Wien's equation as follows:

$$\frac{1}{T} - \frac{1}{T_x} = \frac{\lambda_e \log R}{c_2 \log \mathbf{e}} \tag{8}$$

where R is the transmission of the sector used, in this case 0.5, and the only unknown is the temperature T_x providing the wavelength that is used is known.

To restrict the wavelength range, a so-called monochromatic screen is used in the eyepiece of the pyrometer. Such a monochromatic screen is necessary for two reasons: first, at times it would be difficult to make a brightness match without such a screen, and second, when it is necessary to calculate a temperature from a certain brightness, as measured by an optical pyrometer, some knowledge of the wavelength used is necessary. A red glass screen is used for the most part because better red glass filters are available, and also when extrapolations are necessary, a sector of larger transmission can be used with a filter giving the longer wavelength. By using a series of sectors having transmissions that range from about 80% to about 0.5%, the pyrometer was calibrated from 1823°K to about 1267°K, thus overlapping the calibration point obtained by direct observations on the blackbody at the temperature of melting gold. The value obtained for the melting point of gold by extrapolation down from the palladium point did not check with the calibration point obtained with the furnace held at the temperature of melting gold and finding the reason for this was an interesting special investigation. Later this error was shown to be due to two causes. A part was due to the use of the wrong value for the wavelength of the red glass filter.

As a result of a special investigation (*4*), it was shown that the wavelength one should use is what has been called the effective wavelength (λ_e)—defined as the wavelength for which the ratio of the intensities of blackbody radiation, for any two temperatures, calculated by using the Wien equation and this wavelength are the same as the ratio of the measured brightness of a blackbody for the same two temperatures using the filter in question in the eyepiece of the

pyrometer. Such effective wavelengths can be calculated from the spectral transmission of the filter and other known relations by the use of the following equation:

$$\frac{\int_0^\infty J(\lambda T_1)\cdot T_\lambda \cdot K_\lambda \, d\lambda}{\int_0^\infty J(\lambda T_2)\cdot T_\lambda \cdot K_\lambda \, d\lambda} = \left[\frac{J(\lambda T_1)}{J(\lambda T_2)}\right]_{\lambda_e} \tag{9}$$

where $J(\lambda T)$, see equation (5), represents the energy distribution from the blackbody at temperature T, T_λ the spectral transmission of the filter, and K_λ the spectral luminosity factor. Thus the effective wavelength (λ_e) applies to a certain temperature interval, i.e., from T_1 to T_2 and may be slightly different for other temperature intervals. For equation (8) the effective wavelength is for the interval between T and T_x.

The net result of this work on effective wavelengths of the red glass was to remove one serious source of error from optical pyrometry. The second reason why the temperature as extrapolated down from the palladium point did not

TABLE 1

Summary of Results of Measurement of the Gold-Point Palladium-Point Brightness Ratio

METHOD	NUMBER OF SEPARATE DETERMINATIONS	NUMBER OF MELTS		WAVELENGTH μ	AVERAGE OF RATIO FOUND
		Pd	Au		
Ordinary pyrometer	10	45	45	0.6663	76.9
Spectral pyrometer	3	13	12	0.6018	122.2

check the value obtained directly from the furnace held at the gold point was the value (1823°K) used as the melting point of palladium was too low (see Table 1).

The Melting Point of Palladium. Besides the many checks made on the calibration points at the two standard temperatures by bringing different furnaces to the standard temperature by making melting point determinations, a number of measurements were made (*5*) on the ratio of the brightnesses of the blackbody furnace at the melting point of palladium to that of the brightness of the blackbody at the melting point of gold with the regular optical pyrometer having in the eyepiece a red glass filter whose effective wavelength was accurately determined. Such ratios were also measured using a spectro-pyrometer with the wavelength used selected by the setting of the prism. From the means of such measured ratios (Table 1) of brightnesses, the melting point of palladium was calculated in terms of the melting point of gold and c_2. Such measurements, of course, required a knowledge of the wavelength that is used which, for the glass filter, is its effective wavelength for this temperature range and for the spectro-pyrometer is the wavelength selected by the setting of the prism. As a result of this work, taking the melting point of gold as 1336° and c_2 as 14350μ°,

the melting point of palladium was found to be 1828°K, or 1829°K* if c_2 were taken as 14320μ°.

These two standard points, i.e., the melting point of gold and palladium were determined by the wire method. A small piece of the metal in the form of a fine wire or ribbon was supported in the blackbody cavity of the furnace by a small refractory tube and an electric circuit made through the sample with fine platinum wire leads and when this sample, so mounted as not to touch the supporting refractory tube or the walls of the furnace, melted in the furnace, which was slowly increased in temperature by increasing the current through the heater, and broke the electric circuit, the temperature was taken. The temperature of the uniformly heated cavity was checked by a thermocouple of platinum, platinum-rhodium inserted into the cavity from the rear of the blackbody tube (Fig. 1). The E.M.F. given by the thermocouple was used as an indicator for keeping the furnace at the temperature of the melting palladium by varying the current through one or the other set of heater coils while the readings are being made with the optical pyrometer. This type of thermocouple does not always remain constant in the E.M.F. it gives under these conditions of operation, but the changes are slow enough so that it can be used as an indicator of the temperature of the furnace. Very good reproducibility can be obtained by this method of determining melting points, but some work (*6*) at the National Bureau of Standards has shown that this method of obtaining the melting points of these metals gives values that are slightly higher than those obtained by the freezing point of larger masses of the material.

MAINTAINING THE HIGH TEMPERATURE SCALE

Secondary Standards of Brightness. Because it is a difficult and time-consuming job to operate a blackbody furnace every time it is necessary to check the calibration of an optical pyrometer, it was decided to calibrate tungsten-filament lamps for the brightnesses, as measured with the optical pyrometer, of the blackbody at the two standard points. Two vacuum tungsten lamps, T-100 and T-116, (Fig. 6) with 7½ mil single-loop filaments were used for such secondary standards. A particular part on the lower section of the loop of each filament was selected and the currents through the filament adjusted so that this part of the filament had the same brightness, as measured with the optical pyrometer, as the blackbody for each of the standard temperatures. The part of the filament selected was so uniform in temperature that no difficulty was experienced in measuring and checking the brightness.

The brightness of the blackbody at the two standard temperatures and the accuracy of the transfer of this brightness to the two standard lamps were checked a number of times during a period of about ten years, and thus the value

* As a matter of fact, the data in Table 1 give about 1830°K as the melting point of palladium if c_2 equals 14320μ°. This has been taken as 1829°K however. Some later work (*6*) of the National Bureau of Standards gives 1827°K as the melting point of palladium.

of the currents through these two filaments for brightnesses the same as the blackbody at the palladium point and at the gold point were well determined. These two standard lamps have proven to be valuable as standards for checking the calibration of the optical pyrometers and are still in use for this purpose.

The blackbody furnace has not been operated at the laboratory at Nela Park for several years so the temperature scale has been maintained by the use of these two calibrated standard lamps, T-100 and T-116.

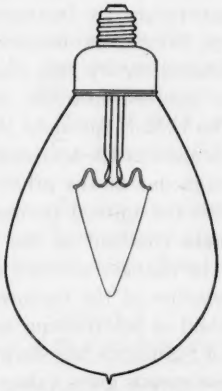

FIG. 6. The filament and bulb of T-100 and T-116. This bulb is about 5 inches in diameter

TABLE 2

Brightness Temperature of a Special Carbon Arc as Measured in Three Laboratories

National Carbon Co.	*3820°K
Nela Park	*3811
National Bureau of Standards	3821

* Corrected to International Temperature Scale since data published by Dr. Chaney.

In 1937 the brightnesses of these two lamps, as measured with the optical pyrometer having the red glass in the eyepiece, were checked at the National Bureau of Standards (*9*), and it was found that the mean brightness of the two filaments for the current that had been used to bring them to the brightness corresponding to the melting point of palladium was that of a blackbody at 1829.6°K on the International Temperature Scale. On this scale the melting point of palladium has been found (*10*) to be 1827°K with c_2 taken as 14320μ°. Since we have been using the mean brightness of these two filaments to correspond to a temperature of 1829°K, using c_2 as 14320μ°, it is to be noted that the temperature in use at Nela Park is in good agreement with the International Temperature Scale.

A Check on the High Temperature Scale. In 1922 the brightness temperature of two tungsten-filament lamps were carefully measured for a number of currents

and sent to the National Bureau of Standards for a check. The temperature of these lamps ranged from 1400 to 2750°K. There was no trend (*7*) in the difference between the temperature scale used at Nela Park at that time and the scale used at the National Bureau of Standards, and in no case was the difference more than about 3°. Another check on the agreement of the temperature scale was made in 1935. Dr. N. K. Chaney (*8*) and others of the National Carbon Company measured the temperature of certain carbon arcs in his laboratory, and a check of the temperature was made at Nela Park and the National Bureau of Standards. The final result of the values for the temperature of the arc found in the three laboratories, all reduced to the international temperature scale, are shown in Table 2.

THE COLOR-TEMPERATURE SCALE

Direct Comparison. As soon as the high temperature scale was set up and the optical pyrometer calibrated, work was started on a determination of the color-temperature scale in terms of the voltages at which selected tungsten lamps must be operated to match in color the blackbody at various temperatures. Since the platinum-wound furnace could not be operated much higher than 1829°K, a carbon-tube furnace was built. This furnace (*11*), shown by the cross-sectional view in Fig. 4, has as a blackbody a graphite disk at the central part of the graphite tube, *A*, about 1.5 cm internal diameter and 25 cm long, which is heated electrically. It was possible to operate this furnace, as constructed, up to a temperature of about 2650°K and still maintain uniform temperature conditions.

The light given by a vacuum tungsten lamp was directly compared in color with the light given by this furnace for temperatures ranging from about 1700°K up to about 2400°K. When making these measurements, the light from one end of the carbon-tube furnace was color matched with that from a vacuum tungsten-filament lamp using the ordinary contrast photometer. The temperature of the furnace was determined at the same time by reading from the other end of the carbon tube using a calibrated optical pyrometer. The graphite disk in the center of the furnace was made very thin to insure that radiation of the same temperature would be obtained from each end of the furnace. A check with another calibrated optical pyrometer showed this to be the case quite accurately.

The carbon-tube furnace was operated at various temperatures and the emitted light color-matched with different selected tungsten-filament vacuum lamps used as comparison lamps. After each set of determinations, the values of the color temperature in terms of the voltage or current of the comparison lamp used were transferred, in terms of their voltage or current, to one or more of several tungsten-filament lamps, among which was lamp T-1, a 120-volt, 100-watt pressed-filament tungsten lamp, which had been used as a color-temperature standard in some previous work (*12*). To show the agreement of the various observations, all the measured points were transferred to T-1 and are shown in Fig. 7, plotted against the voltage of this lamp. Most of the measured

points are within 5° of the curve, the worst deviation being 16°. A number of these points were checked by using one or more of the platinum-wound black-body furnaces at certain temperatures up to 1829°K as a standard for color temperature. These values of color temperature (from 1600 to 2450°K) were then transferred to a 40-watt, spring-supported, straight-filament tungsten lamp, T-122, which has served as the reference standard of color temperatures in this range since about 1920.

In the work on color temperature, it was found, as would be expected, that two tungsten lamps of similar construction required the same ratio of voltage change for the same change in color temperature. Thus, if V_1 and V_2 are the

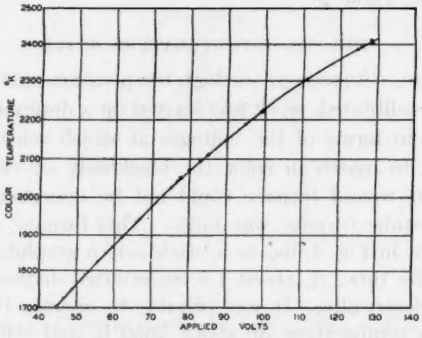

FIG. 7. The relation between color temperature and applied volts from the old standard lamp T-1

voltages required for two similar lamps for a color temperature of T_1, and V_1' and V_2' the voltages for these two lamps for a color temperature T_2, then

$$\frac{V_1}{V_1'} = \frac{V_2}{V_2'}$$

This relation has been used to calculate the color temperature of new color standards for different applied voltages from the color temperature at one voltage by comparison with the voltage-color temperature relation of a lamp already calibrated. The known relation between the applied voltage and color temperature for T-122 has been used as the standard for this purpose for the temperature range from 1600 to 2450°K.

Extending the Color-Temperature Scale. Further work was required to extend the color-temperature scale to 2800°K or even higher. This was done in a different manner. If two sources of continuous radiation so radiate that, when they are color-matched by the method outlined above, they have the same relative spectral distribution to within the errors of observation, the two curves that represent their energy distribution can be made to coincide by changing the intensity scale of one of them. Color matches of such sources can be obtained from a series of measurements of the relative brightnesses of the two sources in

two parts of the spectrum. The measurements of the relative brightnesses can be made with the optical pyrometer, using first a red glass and then a blue glass filter in the eyepiece of the pyrometer, with the pyrometer calibrated for relative brightnesses rather than for temperatures.

About the same time the above measurements were being made, Dr. Worthing (*1*) working at the Nela Park laboratory developed a method for determining the emissivity of tungsten—that is, the relative brightness of tungsten and the blackbody when the two are at the same temperatures. To do this, he constructed a blackbody of a tungsten tube several centimeters long, about 1.3 mm outside diameter, and 0.8 mm inside diameter and mounted it as a lamp filament so that it could be heated electrically. This tube when heated contained blackbody radiation since it is a cavity with uniformly heated walls. Small radial holes about 0.09 to 0.12 mm in diameter were made through the wall of this tungsten tube to serve as openings for observing the blackbody radiation from the inside of the tube (Fig. 4).

Dr. Worthing, using an optical pyrometer, measured the brightness of the blackbody radiation by observations through the small radial holes and the brightness of tungsten by observations on the outer surface of the tube near the small blackbody holes. Since the outer surface of the tungsten tube was at practically the same temperature as that of the inner walls of the tube, the temperature of the blackbody, from these measurements he was able to calculate the emissivity of tungsten at different temperatures.

COLOR MATCHING BY THE RED-BLUE RATIO

The ratios of the red to the blue brightness were determined by observations on a number of blackbody furnaces for a range of temperatures from about 1400°K up to about 3000°K. The standard platinum-wound furnaces were used up to 1829°K, the carbon-tube furnace used for a range of 1600 to 2650°K, and Worthing's tungsten-tube furnace used for temperatures up to about 3000°K.

The logarithms of the ratios of the red brightness to the blue brightness (called the red-blue ratio) were plotted against the reciprocals of the temperatures. The exact location of the curve through the experimental points was determined by means of a least-square solution assuming a curve of the second order. This method was used because it was found rather difficult to decide just where the curve should be drawn. A very nearly linear relation was found. For a blackbody, if monochromatic radiation is used, a linear relation between $1/T$ and log R/B would be expected as can be shown from the Wien equation. Using this resulting equation, one could extend the curve to higher or lower temperatures as necessary. Now if a particular red-blue ratio is obtained from measurements on the radiation of a source being studied, its color temperature under this assumption can be found from the point on this curve that has the same red-blue ratio.

The filament of a vacuum tungsten lamp is all at very nearly the same temperature except the parts of the filament that are cooled by conduction of heat by the supports or leads. Thus by screening out the light that comes from the

parts of the filament that are near the supports or leads, the color temperature-true temperature relation for a uniformly heated tungsten-filament lamp can be determined. The temperature of the filament of a gas-filled tungsten lamp varies from point to point due to the effects of the gas currents within the bulb. Thus one cannot measure directly the red-blue ratio for the total light from a gas-filled tungsten lamp. The average color temperature of a gas-filled tungsten filament lamp can be determined from the red-blue ratio by illuminating a magnesium carbonate block, which has very nearly the same reflection factor for all wavelengths, with the light from the lamp being tested and then measuring the red-blue ratio of the illuminated surface of the magnesium carbonate block. By making corrections for any variation of the reflection factor of the magnesium carbonate block with the wavelength, one gets the red-blue ratio of the total light from the lamp, from which, of course, the average color temperature of the lamp can be obtained.

TABLE 3

Brightness Temperature of Tungsten for Color Match with Carbon at Different Brightness Temperatures by Two Methods

CARBON BRIGHTNESS TEMPERATURE	COLOR MATCHED BY DIRECT COMPARISON	COLOR MATCHED BY RED-BLUE RATIO
1736°K	1686°K	1685°K
1801	1735	1732
1866	1783	1780
1922	1821	1824
1982	1867	1862
2042	1915	1915
2089	1953	1955
2148	2006	2005
2202	2048	2042

A straight, horizontal filament in a gas-filled lamp is at very nearly a uniform temperature, so the color temperature of this straight filament can be determined for a range of currents by the red-blue ratio method. Such a horizontal filament, thus calibrated, with the ends screened, can be color-matched using the photometer with the total light from any tungsten lamp. Using the two methods just described, the color temperature for several selected tungsten lamps such as the 500-watt, 115-volt, tungsten-filament lamp, and the 30-volt, 900-watt, projection lamp were measured. Such measurements were extended to about 3000°K, which is about as high a temperature as one can reach using a tungsten-filament, gas-filled lamp as a standard.

Checking the Red-Blue-Ratio Method. A test (*13*) of color-matching by the red-blue ratio was made for a carbon lamp by first color-matching it with one of the vacuum tungsten lamp standards by the use of the regular photometer, and then determining when the tungsten lamp and the carbon lamp were at a color match by the method of the red-blue ratios. When using the regular photometer, the ends of the filament of each lamp were screened so as to eliminate

errors due to end cooling. The results of this test are given in Table 3, in the first column of which are given the brightness temperatures of the carbon lamp for the different currents used. The results obtained for the brightness temperature of the tungsten for a color match with the carbon filament, using the red-blue ratio, are given in column three. These values are the averages of two sets of readings. The agreement is very good.

TABLE 4

Brightness Temperature of Tantalum for Particular Color Temperature by Two Different Methods of Color Matching

COLOR TEMPERATURE °K	BRIGHTNESS TEMPERATURE	
	Color Matched on Photometer	Color Matched by Red-Blue Ratio
1819	1647	1648
1947	1748	1750
2061	1838	1841
2171	1924	1928
2275	2008	2007
2376	2086	2085
2475	2160	2158

TABLE 5

Relation Between Brightness Temperature and Color Temperature for a Number of Substances

BRIGHTNESS TEMPERATURE	CORRESPONDING COLOR TEMPERATURE FOR						
	Untreated Carbon	Gem	Platinum	Nernst Glower	Osmium	Tantalum	Tungsten
1400°K	1414		1568°	1538	1444	1507	1492
1500	1515		1692	1642	1562	1631	1607
1600	1616	1620	1821	1747	1680	1758	1723
1700	1718	1735	1952	1852	1799	1883	1841
1800	1820	1852	2086	1954	1919	2010	1961
1900	1923	1962		2053	2045	2137	2082
2000	2028	2064		2146	2168	2265	2206
2200	2240	2255		2310	2427	2500	2457
2400					2688	2785	2718
2600							2988
3000							3564

A like set of measurements by the two methods was made for a tantalum lamp. The brightness temperatures obtained by the two methods for a number of color temperatures were in good agreement as can be seen from the results in Table 4.

The red-blue-ratio method of obtaining color temperature was then used to measure the relation between the color temperature and the brightness temperature of treated and untreated carbon, of tungsten, tantalum, osmium, platinum, and the Nernst glower. The relation between the color temperature and the

brightness temperature for these different radiators are shown in Table 5, where in column one are given the brightness temperatures, and in the color columns the corresponding color temperatures for the different radiators.

Accuracy in Measuring Color Temperatures. A question that is often asked is—how accurately can an experienced observer using the contrast photometer make determinations of a color temperature. In order to make a test of this (*14*), three experienced observers matched in color two 40-watt, 115-volt, straight-filament tungsten lamps with spring support, by the substitution method. A standard lamp was kept at a constant voltage and the comparisons set for a color match with it by varying the voltage of the comparison lamp. Five readings of the voltage were taken and averaged. The comparison lamp was then set at this average voltage and the unknown lamp, now on the photometer in place of the standard, was brought to a color match by varying its

TABLE 6

Values Obtained for Color Matching Lamp No. 5 Against Lamp No. 4 by a Number of Observers

OBSERVER	VOLTS FOR COLOR MATCH. MEAN OF FIVE READINGS	MEAN OF THREE SETS	MEAN VARIATION IN VOLTS
F. E. C. 1	103.39		
2	103.60		
3	103.71	103.57	0.19
A. H. T. 1	103.72		
2	103.71		
3	103.66	103.69	0.25
W. E. F. 1	103.80		
2	103.45		
3	103.79	103.68	0.13

voltage, again taking five readings and averaging. This was repeated on three different days with the results as shown in Table 6.

The color temperature of the lamps used in this test was about 2400°K and the illumination on the photometer screen for this test was 5.1 footcandles. The averages for the voltages obtained in each set by each observer for lamp No. 4 to color match lamp No. 5 at 105 volts are given. There is also given the mean variation in volts for the different readings for the different observers. An examination of the table will show that the maximum range in the three sets for any of the experienced observers is less than 0.4 volt. The range in the averages of the three sets for these same observers is only about 0.1 volt. The maximum range in the averages for all the observers is only about 0.4 volt. A change of 1 volt at this point corresponds to a change in color temperature of about 8°K. It can thus be seen that the maximum spread for inexperienced observers corresponds to about 4°K.

The regular procedure in making color-temperature determinations in the laboratory is to make three separate determinations which are recorded in terms

of the voltage applied to the comparison lamp. If the spread of these three voltages is more than 0.5 (when the voltage applied to the comparison lamp is about 100), another reading is taken. A good observer seldom has to take the fourth reading. For a 500-watt lamp operated at a color temperature of 2800 and about 100 volts applied, 0.5 volt corresponds to a difference in the color temperature of about 6°K. Considering this from the spectral distribution, this difference in color temperature makes a relative difference in the red intensity ($\lambda = 0.665\mu$) to the blue intensity ($\lambda = 0.465\mu$) of less than 1.5%.

A measurement was also made to find what accuracy could be expected in determining color temperature for different intensities of illumination on the photometer screen. Various observers made quite a number of color matches for different illuminations on the photometer screen, using in every case two tungsten lamps so that there would be no questions as to the exactness of color match. The range of illumination on the photometer screen was from 1.8 footcandles to 45 footcandles. If there is any difference in the accuracy depending upon the illumination of the photometer screen, this test did not show it.

COLOR MATCH AND SPECTRAL DISTRIBUTION

The relative spectral distribution for several different radiators when color-matched with the blackbody was measured over a wide range of temperatures by measuring the brightness in three parts of the visible spectrum, using a disappearing filament optical pyrometer with a red ($\lambda_e = 0.665\mu$), a green ($\lambda_e = 0.540\mu$), and a blue ($\lambda_e = 0.465\mu$) screen in turn as the monochromatic filter.

The sources studied were color matched by the red-blue-ratio method just described and then the green brightness measured for the same temperature range. If the various radiators studied have the same relative spectral distribution in the visible spectrum as the blackbody when they are color-matched, the corresponding green brightnesses for the different radiators should give the same red-green ratios as the blackbody at these corresponding temperatures. Any differences in this relative red-green brightness would mean that the intensity in this part (green) of the spectrum was either too high or too low for perfect color match. The data on the red-green brightnesses for carbon as compared to the blackbody data fit within the experimental error. This means that when the carbon lamp is color-matched by means of a red-blue ratio, its relative curve in the visible spectrum fits, within experimental error, that of the blackbody at least for these three points in the spectrum. Thus a color match between carbon and a blackbody indicates the same spectral distribution. The value of the green brightness for tungsten does not fit the relative blackbody curve at color match. The observations show that tungsten radiates in such a manner that when its temperature is set to give the same red-blue ratio as the blackbody for a particular temperature, the green part of the spectrum is brighter than that of the blackbody. This difference however is small, being less than 0.5% for a color temperature of 1600°K and increasing to about 1% at a color temperature of 2600°K. For tantalum the difference is in the same direction,

that is, the green part of the spectrum of tantalum is relatively brighter than that of the blackbody when tantalum is set at the same red-blue ratio. This difference is constant and equal to about 1%. The brightness of platinum shows about the same differences as tungsten. Osmium, on the other hand, when its temperature is set to give the same red-blue ratio is relatively less bright in the green part of the spectrum than the blackbody. This agrees with some other observations that osmium appears slightly purple when it is best color-matched with light from a tungsten lamp.

The red, green, and blue brightnesses of the Welsbach gas mantle were measured. The red-blue ratio thus found corresponded to a temperature of about 2800°K. The red-green ratio measurements show that for the mantle the intensity in the green was about 30% too high for an exact color match. Thus, if the curves that represent the spectral distribution for a blackbody at 2800°K and one that represents the spectral distribution of the Welsbach gas mantle be made equal in the red ($\lambda = 0.665\mu$) and in the blue ($\lambda = 0.465\mu$), the two curves tend to differ in the green where the one showing the intensity of the Welsbach mantle would be about 30% higher than the other.

Maintaining the Color-Temperature Scale. After the color-temperature scale was set up at Nela Park, it was maintained up to 2400°K by a number of 115-volt, 40-watt, vacuum tungsten lamps with straight, spring-supported filaments that were calibrated for an applied voltage of 100 by comparison with the original standards.

The color temperature of these secondary standards for any lower applied voltage was obtained by calculation, using the known color temperature-voltage relation of T-122, and the voltage ratio for the standard at 100 to the voltage of T-122 for the corresponding color temperature, and the experimental fact that similar lamps require the same relative change in applied voltage for a definite change in color temperature.

The scale at about 2800°K was maintained by a number of 115-volt, 500-watt, specially constructed tungsten-filament, gas-filled lamp calibrated for a color temperature for 100 volts. Values between 2400°K and 2800°K are maintained in terms of the voltage of comparison lamps that have been calibrated by comparison with standards calibrated for this range by the red-blue-ratio method. Since the comparison lamps are used for many hours, their calibration is apt to change slightly. Corrections for such changes are made by checking the voltage of the comparison lamp for one color temperature, using a color-temperature standard, and calculating the change for other voltages using the relative-voltage method. Thus if the voltage of the comparison lamp for 2800°K has changed 0.3%, then the voltage of the comparison lamp should be changed by the same percentage for any other temperature.

Comparison of the Nela Park Color-Temperature Scale with that of the National Bureau of Standards. The color-temperature scale maintained at Nela Park has been compared several times with the color-temperature scale of the National Bureau of Standards. The first comparison was made (*15*) in 1922 by the interchange of calibrated tungsten lamps with the very good agreement shown in the

first part of Table 7. The National Bureau of Standards at that time had not established a color-temperature scale for the temperature range up to 2400°K, but based their values for this temperature range on calibrated lamps that they had obtained from Nela Park. Their color temperature for the range from

TABLE 7

Comparisons of the Color-Temperature Scale Maintained at Nela Park with that of the National Bureau of Standards

DATE	NELA PARK	N.B.S.	LAMPS
1922	3087[1]	3085	30V–30A projection lamp
	2848[2]	2848	115V–500W lamp
1932	2846	2848	N.B.S. #4444
	2364	2363	N.B.S. #3376
	New National Bureau of Standards Scale		
1935	2816[3]	2847[3]	
1935	2392[4]	2420[4]	
	2155[5]	2174[5]	
1939	2196[6]	2200	
	2399	2400	
	2604	2600	
	2804	2800	
1941	2044[7]	2046	
	2239	2239	
	2723	2727	
	2841	2842	
1941	2842[8]	2839[8]	

[1] Submitted by Nela Park.

[2] Submitted by N.B.S.

[3] Mean of values for three 115V–500W lamps operated at 100V.

[4] Mean of values for three 115V–40W vacuum, spring-supported filament lamps operated at 100V.

[5] Mean of values for three lamps of same type operated at 75V.

[6] Mean of results for two special projection lamps calibrated at the National Bureau of Standards and measured at Nela Park.

[7] Special projection lamp calibated at National Bureau of Standards and measured at Nela Park.

[8] Mean of measurements on three 115V–500W lamp.

about 2800 to 3000°K was set up from certain spectral-energy measurements.

In 1932 measurements were made of the color temperature of two tungsten-filament incandescent lamps that had been calibrated at the National Bureau of Standards again with good agreement as shown in the second part of this table.

The National Bureau of Standards Color-Temperature Scale. In 1934 some extensive work (*16*) was done at the National Bureau of Standards on the calibration of a number of tungsten lamps for color temperature by directly comparing their light output with that from a special blackbody (Fig. 5) at the temperatures of the freezing points of three metals—platinum (2046°K), rhodium (2239°K), and iridium (2727°K). As a result of this work, a color-temperature scale was established for this range and by various methods it was extended up to 3000°K.

When this work was finished at the National Bureau of Standards, three 120-volt, 500-watt, specially made tungsten-filament, gas-filled lamps were sent to the National Bureau of Standards for calibration on this new color-temperature scale. This was in 1935. When these calibrated lamps were returned, they were compared with the Nela Park color-temperature scale with the results shown in the third part of Table 7. The measurements showed that at 2848°K the color-temperature scale established at the National Bureau of Standards was 31° higher than the scale that had been maintained at Nela Park. When this difference was shown to exist, two lots of 120-volt, 40-watt, vacuum-tungsten lamps with straight, spring-supported filaments were sent to the National Bureau of Standards for calibration—one lot for a color temperature of about 2400°K and the other lot for a color temperature of about 2150°K. When these two lots had been calibrated and compared with the Nela Park color-temperature scale, it was found, (see fourth part of Table 7) that at 2420°K, the National Bureau of Standards color-temperature scale was 28° higher than the scale maintained at Nela Park, and at 2150°K, the National Bureau of Standards scale was 19° higher. The assumption was made that the two temperature scales were in agreement at the melting point of palladium (1827°K) so, using this point and the three points checked, a curve was drawn that was used to correct the Nela Park color-temperature scale to the new scale of the National Bureau of Standards. This corrected color-temperature scale has been in use at Nela Park since 1935.

In 1939 two special projection lamps that had been calibrated for color temperature at the National Bureau of Standards were measured at Nela Park in terms of this corrected temperature scale with the results shown in the fifth part of Table 7. Again very good agreement was found.

In 1941 a special projection lamp was obtained from the National Bureau of Standards that was calibrated for color temperature for a range of voltages. This was compared with the scale then maintained at Nela Park with the results shown in the sixth part of Table 7. Also, in 1941 three 120-volt, 500-watt, gas-filled lamps were sent to the National Bureau of Standards for calibration. When these lamps were returned, they were compared with the three standards calibrated at the National Bureau of Standards in 1935 with the results shown in the last part of this table, which shows a difference of only 3° between these two sets of lamps after one had been used as a standard for about six or seven years.

Check on the old Color-Temperature Standards. Just recently some measure-

ments were made on the color temperature of the old color standards T-1 and T-122 with the results shown in Table 8. The first calibration of T-1 was made for a voltage of 44.15 at the National Bureau of Standards in 1908 and was given in 1910 by Dr. E. P. Hyde (*12*). In 1912 Dr. Worthing made a calibration of this lamp for three additional voltages by calculation using spectrophotometric data. These additional values shown in the second column of Table 8 were based upon the value for 44.15 volts. The various calibrations of this lamp for color temperature show very good agreement. The values found for T-122 in the recent calibration agree over the range checked almost within the accuracy of making such measurements.

TABLE 8

Color Temperature Calibrations of Lamps T-1 and T-122

	VOLTS	1912*	1917‡	1942††
T-1	115.0	2321°K	2332°K	2332°K
	91.2	2146	2160	2162
	67.0	1944	1947	1948
	44.15	1689†	1696	1696

	VOLTS	1920§	1942††
T-122	115.0	2451°K	2453°K
	108.5	2398	2400
	98.5	2320	2318
	80.0	2166	2167
	60.0	1976	1974
	40.0	1720	1720

* Values obtained by A. G. Worthing from spectrophotometer measurements, starting with value at 44.15 volts. Reduced to $c_2 = 14320$.

† Value given by E. P. Hyde in 1910.

‡ As calibrated in 1916 by comparison with carbon-tube blackbody furnace, $c_2 = 14320$.

†† As measured in 1942, corrected to 1916–1920 color-temperature scale.

§ From original calibration.

The 120-volt, 500-watt, specially constructed tungsten lamps that are used for color-temperature standards are calibrated for 100 volts applied and are never used at a higher temperature. The same thing is true for the vacuum tungsten lamps used for color standards for 2400°K and lower. When it is remembered that at 115 volts applied, these lamps would have a life, as light sources, of 1000 hours and that a lowering of 5 in the voltage doubles the life, one can see that if they are never operated at a voltage higher than 100 they should have a very long life as color standards. Some work by Dr. D. B. Judd (*17*) at the National Bureau of Standards shows that such lamps (115-volt, 500-watt, gas-filled, tungsten-filament) change by less than 0.1°K per hour of operation at this color temperature (2800°K), and that the 115-volt, 40-watt vacuum lamp, when operated at a color temperature of 2400°K, changes about

0.06°K per hour of operation. The results of these intercomparison and check measurements of T-1 and T-122 and the tests by Dr. Judd just cited show that the color-temperature scale can be maintained for temperatures up to 2800°K quite satisfactorily by the use of the various types of tungsten lamps.

Color-Temperature-Altering Filters. Again, it became necessary to extend the color-temperature scale or maybe one had better say it became necessary to measure the color temperature of certain lamps that were above 3000°K in color temperature, which is higher than tungsten-filament comparison lamps can be operated for an appreciable time without their calibrations changing. One method of extending the color-temperature scale is to use color-temperature-altering filters. Such filters may be used in front of the secondary standards with the transmission of the filter so selected that the transmitted radiation will appear to be radiation from a source at a higher temperature. For this purpose blue filters are necessary. Also, a selected filter may be used in front of the source at a higher color temperature with the transmission of the filter so selected that the transmitted light has the color of that from a source at a lower temperature. Such filters are yellow in thin and red in thicker layers. Thus either a blue filter may be used to raise the apparent color temperature of the cooler source, or an orange-red filter used to lower the apparent color temperature of the source at higher temperature. The former arrangement (i.e., blue filter) has the advantage of being combined with a source of known energy distribution, and the disadvantage of reducing still further the apparent brightness of the source of lower brightness.

Within the range of validity of the Wien radiation law, there is a simple relation between the wavelength (frequency) and transmission coefficient of such a filter, as shown by the following:

$$J_{H\lambda} = Ac_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_H}}$$

$$J_{L\lambda} = Ac_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T_L}}$$

where $J_{H\lambda}$ is the spectral radiant intensity at wavelength λ for the source at the higher color temperature T_H, and $J_{L\lambda}$ the spectral intensity for the source at the lower temperature T_L, as given by Wien's equation. Dividing the second equation by the first gives

$$\frac{J_{L\lambda}}{J_{H\lambda}} = e^{\frac{c_2}{\lambda}\left(\frac{1}{T_H} - \frac{1}{T_L}\right)}$$

where $J_{L\lambda}/J_{H\lambda}$ is the transmission of the filter for wavelength λ. Taking logarithms of both sides of this equation gives

$$-\log\left(\frac{J_{L\lambda}}{J_{H\lambda}}\right) = \frac{c_2 \log e}{\lambda}\left(\frac{1}{T_L} - \frac{1}{T_H}\right) \tag{10}$$

The left-hand member of equation (10) is the logarithm of the transmission (the optical density) of the filter for any wavelength λ, and the right-hand

member gives this optical density as the product of the frequency (reciprocal wavelength) and the reciprocal difference in color temperature of the sources (microreciprocal degrees or *mireds*) multiplied by a constant.

Hence, a filter whose optical density ($-\log$ transmission) is given by an equation of the form of (10) will convert blackbody radiation of one temperature to blackbody radiation at some lower temperature (for intensity as well as for spectral distribution). As shown by the right-hand member of this equation, the optical density of such a filter for any wavelength is proportional to the frequency ($1/\lambda$) of the radiation. The more absorbing the filter, the greater the (reciprocal) difference in color temperature. Since two sources that are at the same color temperature do not necessarily have the same light intensity, and in making color temperature determinations it is customary to make an independent match of intensity before color matching, it is possible to use a filter as a color-temperature-altering filter, whose optical density is any linear function of the frequency. If the constant of proportionality of equation (10) be made negative, the resulting blue filter will raise the apparent color temperature of the light from any source that passes through it. That is, it will make the radiation more blue. Such a filter can be correct only over a limited spectral range, (which may, however, include all the visible) because at some short wavelength the computed transmission will exceed 100%. After the radiation has passed through a blue filter, used to extend the color-temperature scale, it may or may not have the same intensity as that of the source at higher color temperature, which now the transmitted radiation matches in color.

Since the temperatures of the sources appear only in the factor $(1/T_L - 1/T_B)$, the same filter can be used, starting from any temperature within the range of validity of the Wien radiation law, to convert to the distribution appropriate to some lower (respectively higher if a blue filter is used) color temperature. Thus a blue screen that will change the color of the radiation of a blackbody at 2500°K to that of a blackbody at 3000°K will transform the color of the light from a blackbody at 2600°K to that from a blackbody at 3145°K, etc. The extension is obtained from the fact that the difference between the reciprocal of the two temperatures is constant for a filter that has exactly the right transmission for this purpose. For any blue glass that one can find, in general, this difference is not a constant, but varies with the temperature. For such blue filters as have been experimented with, this difference between the reciprocals of the initial and extended temperature varies almost linearly with the initial temperature; hence, to find the constants for these filters, they must be calibrated for at least two temperatures.

Table 9 has been prepared to show how the spectral transmission of an ideal blue or orange-red color-temperature-altering filter may be calculated from the initial color temperature and the color temperature of the radiation after it has passed through the filters. Suppose it is desired to have a blue filter that will transform the light from a 120-volt, 15-watt, vacuum tungsten lamp (color temperature 2500°K) to the same color as that from a 120-volt, 500-watt, gas-filled tungsten lamp (color temperature 2960°K). The first column of Table 9

gives the wavelengths and in the second column the relative spectral distribution (Wien's equation) for the blackbody at the color temperature of the 15-watt lamp (2500°K) and in column three, like data are given for the blackbody at the color temperature of the 500-watt lamp (2960°K). Now the assumption will be made that the transmission of the blue filter at wavelength 4000Å is 95%. When this filter is in front of the 15-watt lamp, the intensity of the radiation for this wavelength (4000Å) that is transmitted is 0.95 times 0.584 or 0.555. Since there has to be an intensity match on the photometer screen to set for a color match, the intensity of the radiation for the 500-watt lamp at this wavelength will have to be reduced to equal that from the 15-watt lamp as transmitted by

TABLE 9

Data Illustrating the Method of Calculating the Spectral Transmission of a Color-Temperature-Altering Filter for Changing the Light from a Source at a Color Temperature of 2500°K (Column 2) to that of a Source at 2960°K (Column 3) and Vice Versa

WAVELENGTH	RELATIVE SPECTRAL INTENSITY FOR SOURCE AT		§	†	‡
	2500°K	2960°K			
4000Å	.584	41.2	.555*	.950	.0141
4500	1.592	87.2	1.176	.740	.0182
5000	3.360	150.5	2.030	.604	.0223
5500	5.916	224.4	3.028	.512	.0263
6000	9.125	301.8	4.070	.446	.0303
6500	12.75	376.5	5.070	.398	.0338
7000	16.53	441.3	5.950	.360	.0375
7500	20.21	495.5	6.680	.330	.0408

* Intensity from source at 2500°K for wavelength = 4000Å after it has passed through a filter that has a spectral transmission of 95% for this wavelength.

§ Intensity of light from source at a color temperature of 2960°K (column 3) reduced at each wavelength the amount necessary—a factor of 74.2—to make the intensity at wavelength = 4000Å the same as that from source at 2500°K (column 2) after it has been reduced by a filter that has a transmission of 95% for this wavelength.

† Calculated transmission of blue filter.

‡ Calculated transmission of yellow filter.

the filter; that is, it will have to be reduced by a factor of (41.20 divided by 0.555) 74.2 by some means such as moving this lamp farther away from the photometer screen, which will reduce the intensities for all other wavelengths by the same amount. The figures in column four of this table are the intensities of the radiation from the 500-watt lamp at a color temperature of 2960°K (column three) reduced by this factor (i.e., 74.2). The spectral transmissions of the filter are the values of the reduced intensities in column four divided by the values of the intensities in column 2, wavelength by wavelength, and are shown in column five. For this range in color temperature, that is, from 2500 to 2960°K, the spectral transmission of the blue glass ranges, as shown, from 0.95 at 4000Å to 0.33 at 7500Å. It is to be noted that the calculated transmission of this filter would be more than 100% for wavelength 3500Å.

If one wanted an orange-red filter to transform the spectral distribution of the radiation from the 500-watt lamp to equal in color that from the 15-watt lamp, the values of the transmission at different wavelengths are to be obtained by dividing the values of the intensities in column two by those in column 3, wavelength by wavelength, which gives the transmission as shown in column six.

A filter whose spectral transmissions were any (possible) multiple of those given in column five or six would serve as a color-temperature-altering filter since the resulting constant difference in intensity could be taken care of in setting for equal intensity.

No actual filter has been found whose optical density is an accurately linear function of frequency even within the visible spectrum. On account of the three-dimensional character of human color vision, it is not too difficult to find a filter which will enable a particular observer to match a particular pair of sources, but to get a filter that will give a color match for a source at any color temperature which will appear correct to any observer requires a filter whose absorption curve lies very close to the theoretical linear relation between optical density and frequency. In general, blue filters are used to extend the color-temperature scale rather than orange-red filters because, to date, better blue filters are available.

Color-Temperature-Altering Filters in Use. Some years ago the late Norman MacBeth furnished the laboratory with a special blue glass that was found to be satisfactory for extending the color-temperature scale. A good color match with the light from a tungsten lamp, after being transmitted through this screen, with the light from another tungsten lamp at a higher color temperature was possible. Check readings could be made with a fair accuracy, but observers never reported a perfect color match and different observers did not agree in the readings with this filter. This glass had such a spectral transmission that with a thickness of about 1.3 mm, it changed the color of the transmitted light from a lamp at 2500°K to practically the same color as that from another tungsten lamp at 3333°K.

Mr. A. H. Taylor of the Lighting Research Laboratory, Nela Park, obtained some blue glass from the A. H. Dombrink Company, Oakland, California, that is very satisfactory for extending the color-temperature scale. A sample of this glass about 3 mm thick (B-13) is now used in the laboratory as a standard blue screen for extending the color-temperature scale. Its spectral transmission is shown in Fig. 8. This glass changes the color temperature of the light from a lamp at 2500°K to that from a lamp at 2965°K. The extrapolation constant for different temperatures (i.e. $1/T_1 - 1/T_2$) is shown in Fig. 9. Curve B shows the calculated values using the I.C.I. color coordinates and curve A gives the values found for one of the observers now using the blue glass. Further extension of the color-temperature scale is obtained either by increasing the color temperature of the comparison lamp (up to about 2800°K) or by using two pieces of glass in front of the comparison lamp. After the light from a tungsten lamp at a color temperature of 2500°K passes through two filters similar to *B*-13, it has the same color as that from another lamp at 3640°K. Although

the observers report a good color match of the light from a tungsten lamp with the light from a second tungsten lamp after the light has passed through this filter and can make and repeat color-match settings very accurately, comparable to like settings without the filter, different observers do not agree in their measurements, which shows that even this is not an ideal filter for this purpose.

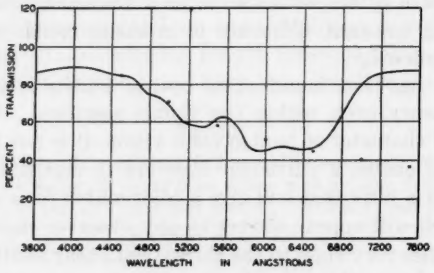

FIG. 8. Spectral transmission of color-temperature-extending filter B-13. The points show the spectral transmission (made equal to that of B-13 at wavelength = 4500Å) of an ideal blue filter of the same color-temperature-extending value as B-13. Note that the spectral transmission of the ideal filter will become greater than 100% for wavelength = 4000Å if it is to be the same as that of B-13 at 4500Å.

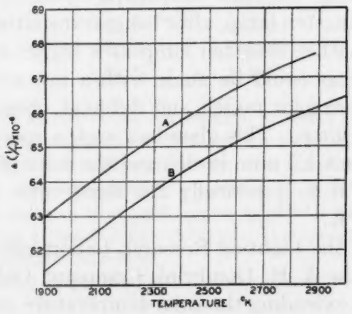

FIG. 9. The extrapolation constant of the blue glass (B-13), whose spectral transmission is shown in Fig. 8, as a function of the initial temperature. Curve B, calculated from I.C.I color coordinates; Curve A, measured values for the operator at present using this filter.

Color Temperature and Characteristics of Lamps. As soon as the color-temperature scale was set up, work was started on correlating the characteristics of the various lamps with their color temperature. As has been pointed out, the color of tungsten-filament lamps may be quite accurately specified by giving their color temperature. This is not the case for lamps in colored bulbs; even the color of the blue-bulbed "daylight" lamp is not accurately represented by a blackbody at any temperature, since even the best available blue glass is far from being a perfect color-temperature-altering filter.

Because of the three-dimensional character of human (photopic) vision, three specifications are necessary and sufficient to describe the color of an object, i.e., in the case of a light source, two specifications beside the luminous intensity. This may be done by giving two I.C.I. trichromatic coefficients (*18*) (x and y) beside the luminous intensity; but for sources approximately like some one of the phases of daylight a convenient specification of the chromaticity (*18*) is in terms of the color temperature and the subjective difference from the nearest blackbody color. In addition to carbon- and tungsten-filament lamps, this method is applied to "daylight" tungsten lamps; and to the "white", "daylight" and "soft white" fluorescent lamps, with color temperatures respectively 3500°K, 6500°K and 4000°K−45 j.n.d.* Since the color of the light from the fluorescent lamp is affected not only by the proportions of the fluorescent materials, but by the conditions of their manufacture, it is possible to regulate the color with a precision difficult if not impossible to obtain with colored bulbs and incandescent filaments.

The true temperature of tungsten is lower than the color temperature, being about 44° lower at a true temperature of 2000°K, about 84° lower at 2500°K, which difference increases to about 121° at 3000°K. The color temperature of a lamp always means the average color temperature of the light from the entire filament, which is, of course, lower than the color temperature of the part of the filament that is at maximum temperature. The true temperature given is generally for the part of the filament that is at the maximum temperature. Thus the difference between the true temperature and color temperature of a tungsten lamp is less than that for tungsten. Indeed, for lamps that have filaments of such shape that there is a wide variation in temperature, the maximum true temperature may be higher than the average color temperature.

The characteristics of a number of the lamps used for general lighting purposes are given in Table 10, together with their color temperature. This table also contains data on the CX lamps which are used for the production of a mild ultraviolet and as sources of infrared radiation. These lamps, as shown, are operated for a life of 500 hours, which means a higher temperature than the regular lamp of corresponding wattage, and thus a larger percent of the input is in the ultraviolet region. Also, to permit more of the ultraviolet radiation to be used, the bulbs are made of a glass that has a high transmission for this part of the spectrum. Data are also included on the street-series lamps. These lamps, as the name indicates, are used for street-lighting purposes and are operated in series on a constant current. The fourth part of this table contains data on a number of lamps used for airport-lighting, flood-lighting, and spot-lighting purposes.

The characteristics of a number of lamps used for the various photographic purposes are given in Table 11. These include first, lamps for use as sources for taking pictures, such as the photoflood lamps, which operate at an initial color

* i.e., the lamp is less green than the blackbody at 4000°K and differs from it by 45 times the least perceptible difference in "chromaticity." The other two lamps are—within the manufacturing tolerance—on the blackbody locus (19).

temperature of 3425°K. These lamps have a very short life since here the need is for as much light as possible for the wattage used. Next, data are

TABLE 10

Color Temperature and Efficiency of Some Lamps Used for Lighting Purposes

LAMP WATTS	LIFE (HRS.)	LUMENS PER WATT	COLOR TEMPERATURE °K
Some 120V lamps for General Lighting			
6*	1500	6.6	2375
10*	1500	7.9	2450
15*	1000	9.2	2510
25*	1000	10.4	2550
40	1000	11.6	2775
60†	1000	14.0	2805
75	750	14.9	2855
100†	750	16.2	2870
150	750	17.2	2895
200	750	18.5	2930
300	750	19.5	2940
500	1000	20.0	2960
750	1000	19.8	2955
1000	1000	21.2	3020
1500	1000	21.9	3060
2000	1000	22.0	3065
CX Lamps			
60		13.9	2830
250		18.9	2940
500		21.5	3040

LAMP AMPS.	LUMENS	LUMENS PER WATT	COLOR TEMPERATURE °K
Street-Series Lamps‡			
6.6	1000	16.2	2935
6.6	2500	17.5	2955
6.6	4000	19.0	2975
6.6	6000	19.4	2980
15	4000	19.7	3020
20	6000	20.4	3050
20	10000	20.6	3035
20	15000	21.0	3040
20	25000	20.6	3030

LAMP VOLTS	LAMP WATTS	LIFE (HRS.)	LUMENS PER WATT	COLOR TEMPERATURE °K
Airport Lighting				
32	1500	100	28.0	3330
120	5000	75	33.0	3380
120	10000	75	33.0	3380
Flood Lighting				
120	250	800	15.4	2850
120	400	800	16.2	2875
120	500	800	17.5	2915
120	1000	800	19.5	2975
120	1500	800	20.0	3000
Spot Lighting				
120	250	200	17.6	2915
120	400	200	20.0	2960
120	500	200	20.0	2960
120	1000	200	22.5	3035
120	2000	200	24.0	3080

* Vacuum lamp.

† Coiled-coil filament.

‡ These lamps are designed for 2000 hrs. life.

included on lamps for taking color pictures on Type B Kodachrome, which requires a source giving light at a color temperature of 3200°K. The last part

TABLE 11

Some Characteristics of a Number of Lamps for Photographic Purposes

LAMP	VOLTS	WATTS	LUMENS PER WATT	LIFE (HRS.)	COLOR TEMPERATURE °K
Photoflood:					
No. 1	115	250	31.4	6	3425
No. 2	115	500	31.6	9	3425
No. R2	115	500		9	3425
No. 4	115	1000	31.9	12	3425
Movieflood	115	2000	32.1	20	3425
Color Photography:					
3200°K Lamps* (Initial color temperature 3250°K)		500	27.0	40	
		1000	27.4	60	
		1500	27.6	70	
		2000	27.8	80	
		5000	28.0	160	
CP Lamps* (Color temperature 3380°K)		2000	32.0	35	
		5000	33.0	75	
		10000	33.0	75	

* Under normal conditions these lamps are available for a number of voltages, but now there are some restrictions both as to the voltage and the wattage of these types of lamps that are available.

TABLE 12

Some Characteristics of a Number of Projection Lamps

LAMP	BULB	FILAMENT	LIFE	LUMENS PER WATT	COLOR TEMPERATURE °K	CANDLEPOWER*
50 watt	T8	CC-13	50 hrs.	16.2	2950	87
100	T8	CC-13	50	19.2	3015	209
200	T8	2-CC-8	25	23.5	3145	472
200	T10	CC-13	50	21.2	3055	395
300	T10	2-CC-8	25	24.5	3155	750
400	T10	C-13-D	25	25.0	3170	1250
500	T10	C-13-D	25	26.0	3240	1850
500	T20	C-13	50	26.5	3175	1490
750	T12	C-13-D	25	27.0	3280	2850
900†	T10	C-13	200	26.5	3200	2700
1000	T20	C-13	50	28.0	3230	3230
1000	T20	C-13-D	25	28.0	3280	4100
1000	T12	C-13-D	10	32.0	3375	4750
1500	T20	C-13-D	25	28.5	3340	6740
2100‡	T24	C-13-D	50		3315	7490
5000	G64	C-13	75	32.7	3380	18500
10000	G96	C-13	120	32.8	3380	37000

* In direction of projection.

† 30 volts.

‡ 60 volts; all others 115–120 volt lamps.

TABLE 13

Characteristics of Photo Enlarger Lamps

(White Bulb)

LAMP	BULB	LIFE IN HOURS	LUMENS PER WATT	COLOR TEMPERATURE	BULB BRIGHTNESS	CANDLE-POWER*
No. 115† 32W	S-11	50		3175	4.1 c/cm²	46.0
No. 113 50W	S-11	50	15.0	2765	4.6	52.5
No. 111 75W	S-11	25	15.0	2850	7.8	76.0
No. 211 75W	A-21	100	17.3	3050	2.8	118
No. 212 150W	A-21	100	20.7	3135	6.5	287
No. 213 250W	A-21	2	32.0	3430	13.8	607
No. 301 300W	PS-30	100	22.3	3180	5.5	501
No. 302 500W	PS-30	100	23.2	3195	8.4	795
No. 303 500W	PS-30	6	31.6	3350	10.9	1035

* In direction used.

† 5.25 volts; all others 115 volts.

TABLE 14

Some Characteristics of a Number of Photocell Exciter Lamps

VOLTS	AMPS.	LUMENS PER WATT	COLOR TEMPERATURE
8.118	2.0	9.1	2645
8.363	4.0	20.9	3115
8.717	4.0	22.3	3185
9.850	7.5	21.5	3105
10.285	5.0	21.4	3095
4.091	.75	10.8	2955

TABLE 15

Characteristics of a Number of Miniature Lamps

LAMP	VOLTS	WATTS/ SPH. CANDLE	COLOR TEMPERATURE °K
Flashlight PR3	3.57	1.17	2805
Flashlight 31	6.15	0.87	2790
Flashlight 248	2.40	1.35	2675
Flashlight 605	6.15	0.88	3020
Radio panel 44	6.15	1.5	2400
Grain-o-wheat	1.5	6.0	2100
Christmas tree	115.	1.0	2600
		LUMENS/WATT	
Sewing machine	115.	7.5	2345
Sign-clear	115.	8.0	2400

of the table gives data on sources to be used with technicolor films, which sources are based on lamps operated at a color temperature of 3380°K.

Table 12 shows data on the characteristics of a number of lamps used for pro-

jecting moving pictures in various types of machines for this purpose. The characteristics of a number of photoenlarger lamps designed for use with the various type enlarging devices are given in Table 13. Characteristics of a number of lamps used as photocell exciter lamps for taking and projecting talking movies are given in Table 14, as related to their color temperature. The last table, which is Table 15, gives data on a number of miniature lamps.

The data given in the last six tables show that tungsten lamps have been made and offered to the public for a wide range of color temperature, i.e., from about 2100°K to about 3425°K, which means a variation in life from several thousand hours to only a few hours. These data have been obtained as a result of measurements extended over several years and the data have been kept up to date by making whatever corrections are necessary to keep in line with the various improvements in the lamp characteristics made by the lamp engineers. No attempt has been made to indicate in these tables which lamps are not now made on account of curtailments due to the present emergency.

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THE VEGETATION OF IDAHO[1]

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ABSTRACT

The vegetation of Idaho is discussed. Eight plant associations are given and the distribution, climate, elevation and principal plant species of each association are listed. These associations are alpine tundra, spruce-fir, larch-pine, yellow pine-Douglas fir, pinon-juniper, bunchgrass, sagebrush and salt desert shrub. Lodgepole pine is listed as a subclimax.

The bunchgrass has largely been destroyed by overgrazing and has been replaced with sagebrush. The sagebrush type which occupies the southern part and more than half the area of the state is discussed in some detail and a comparison drawn between its original and present condition. The pinon-juniper and salt desert shrub have also been changed by grazing.

INTRODUCTION

Idaho is one of the largest states in the union and has an area of 83,888 square miles. It stretches for nearly 500 miles from Utah and Nevada to Canada. In the central part is the largest "primitive area" left in the United States and it is said that some places have never been seen by white man. Many areas may be entered only by pack train or on foot. Some of the state has never been carefully explored or botanized. Eight plant associations occur in the state and it offers a fertile collecting ground for the collector of new plant species.

No adequate key to the flora of the state has been published. Howell's flora (*4*) included Idaho, but it is out of date and out of print. Tidestrom's "Flora of Utah and Nevada" (*14*) and Rydberg's "Flora of the Rocky Mountains" (*10*) cover parts of the state, but are also out of print. The "Flora of southeastern Washington and of adjacent Idaho" by St. John (*13*) serves well for the northern part and "A manual of the higher plants of Oregon" recently published by Peck (*8*) is excellent for the southwestern part. All of the above publications include many species not found in Idaho. Unpublished catalogs of the flora have been prepared by Davis (*2*) and Myers (*7*).

The general aspects of desert vegetation including southern Idaho have been discussed by Clements (*1*) and Shreve (*12*). Senate Document 199 (*16*) and Mollin (*5*) discuss range sections of the west, but are in considerable disagree-

[1] This study was begun when the author was a member of the faculty of Boise Junior College, Boise, Idaho.

ment. Shantz and Zon (*11*) consider the original vegetation of the state in their study of the natural vegetation of the entire country.

FACTORS AFFECTING IDAHO VEGETATION

The climate of Idaho has many extremes. The growing season varies from 200 days near Lewiston on the northwestern edge of the state to 40 days in the highest mountains. In some locations freezing temperatures occur in every month. The temperature is generally milder than that of states east of the Continental Divide in the same latitude since Idaho is influenced by the westerly winds from the Pacific Ocean. The rainfall varies from 8 inches along the Snake River in southwestern Canyon, Owyhee and Elmore counties to 50 inches in parts of Shoshone and Clearwater counties. In the southern part of the state 2 to 3 drought years out of every 10 must be expected (*16*).

The altitude affects the temperatures, precipitation and length of the growing season. The lowest elevation is 783 feet in Nez Percé County and the highest, 12,665 feet in Custer County. Much of the state lies between 2500 and 6500 feet.

The flora is affected by its contacts with floras from other parts of the west. In Owyhee County is a pinon-juniper woodland, an extension of a southwestern type; in the north is a western larch-western white pine forest, a Pacific Coast association; alpine tundra is on the tops of the highest mountains and many arctic species are included. Below the tundra is a subalpine forest which is characteristic of western Canada. Most of the forest vegetation is similar to that of the Rocky Mountains.

In the southern part there have been changes in the bunchgrass and sagebrush due to agriculture and overgrazing. Here there have been many additions to the flora. Many of these plants are aliens and plants brought in with agricultural seed from the east.

PLANT ASSOCIATIONS

The following classification of Idaho vegetation follows that of Weaver and Clements (*17*). The location of these associations is indicated in Fig. 1 (*11*).

TUNDRA CLIMAX

I. Tundra Formation

1. Alpine Tundra: *Carex-Poa* association.

Alpine tundra is found on the tops of the highest mountains above the spruce-fir forests in the Bitter Root and Salmon River mountains. The elevation is above 11,000 feet. Temperatures are low and the growing season is 40 days or less. Snow remains on the ground nearly the entire year. The principal plants are included in the folowing genera: *Carex, Poa, Calamagrostis, Festuca, Phleum, Luzula, Caltha, Primula, Ranunculus, Mertensia, Pentstemon, Salix, Claytonia, Anemone, Lesquerella, Saxifraga,* and *Silene acaulis.*

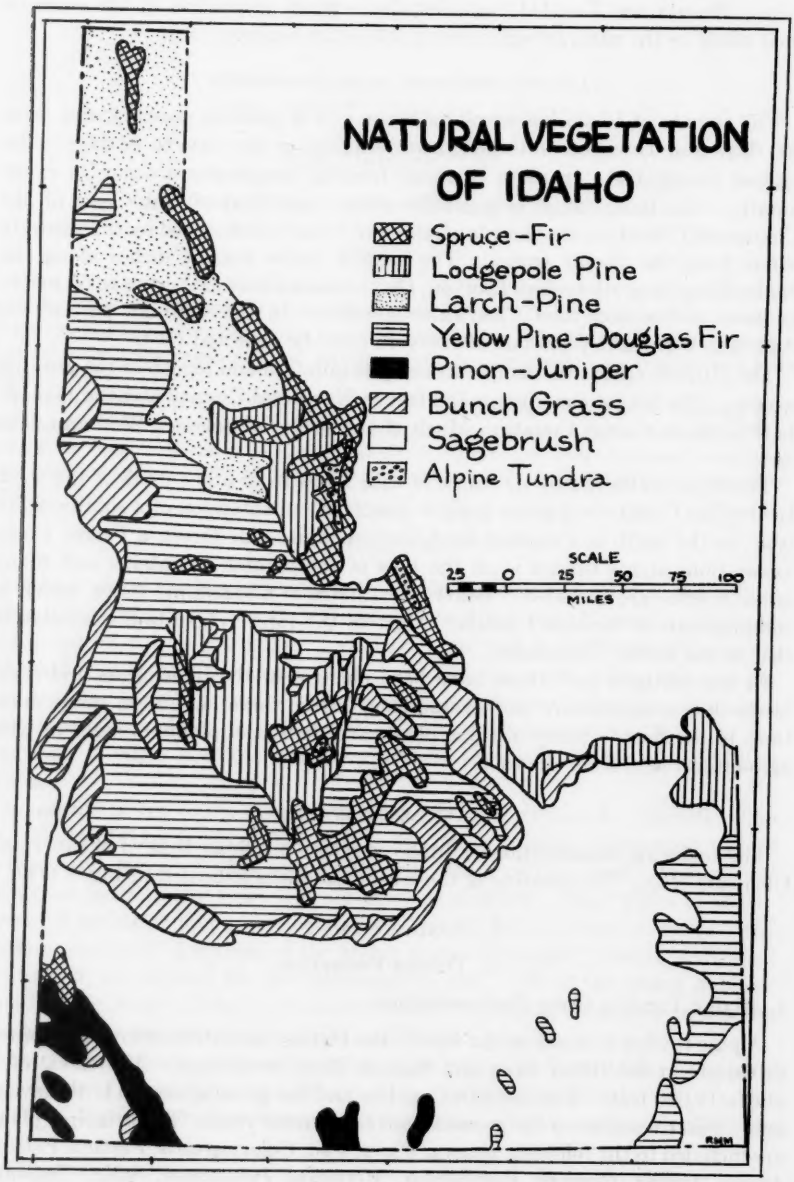
NATURAL VEGETATION
OF IDAHO
Spruce-Fir
Lodgepole Pine
Larch-Pine
Yellow Pine-Douglas Fir
Pinon-Juniper
Bunch Grass
Sagebrush
Alpine Tundra
SCALE
25 0 25 50 75 100
MILES
RMM

FIG. 1

FOREST CLIMAXES

II. Subalpine Forest. *Picea-Abies* Formation

2. Spruce-fir Forest. *Picea-Abies* association.

A spruce-fir forest is found from 8000 to 12000 feet elevations in parts of Blaine, Custer, Lemhi, Idaho, Clearwater, Shoshone, Benewah, Bonner and Boundary counties. The precipitation is usually more than 20 inches. The principal trees are Engelmann spruce (*Picea Engelmanni*), alpine fir (*Abies lasiocarpa*). Limber pine (*Pinus flexilis*), and lodgepole pine (*Pinus contorta Murrayana*) are also common. The forbs* include species of *Dentstemon, Castilleja, Mertensia, Fragaria, Pedicularis, Orthocarpus, Erythronium, Mimulus, Dodecatheon, Saxifraga* and *Claytonia.* Several species of *Ribes* are found.

2a. Lodgepole pine subclimax. *Pinus* consocies.

Large areas in Custer, Boise, Valley, Lemhi, Idaho, Clearwater, Clark, and Fremont counties are covered with lodgepole pine (*Pinus contorta Murrayana*). This forest is a subclimax due to fire and probably would be replaced with spruce and fir at its upper limits and with yellow pine and Douglas fir at the lower elevations. It requires more than 18 inches of precipitation.

III. Coast Forest. *Thuja-Tsuga* Formation

3. Larch-pine Forest: *Larix-Picea* association.

This association is seen at its best in this country in northern Idaho. In places it may be nearly a pure stand of white pine. It is found in Boundary, Bonner, Kootenai, Benewah, Shoshone, Clearwater and Idaho counties. The dominants are western larch (*Larix occidentalis*) and western white pine (*Pinus monticola*). Red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) are also found.

IV. Montane Forest. *Pinus-Pseudotsuga* Formation

4. Petran Montane Forest: *Pinus-Pseudotsuga* association.

This forest is characteristic of the drier slopes below the spruce-fir forest and above the bunchgrass and sagebrush. It ranges from 4,000 to 8,000 feet and is found in most of the central and northern counties. At the upper elevations Douglas fir (*Pseudotsuga mucronata*) is most abundant. Yellow pine (*Pinus ponderosa*) is more characteristic of the driest parts of the forest and extends lower than Douglas fir. The precipitation is usually from 15 to 25 inches.

Species of *Ribes, Rosa, Salix, Ceanothus, Clematis* and *Cornus stolonifera* and *Philadelphicus Lewisii* (Idaho's state flower) are important shrubs. The forbs include species of *Geranium, Pentstemon, Mertensia, Agoseris, Senecio, Antennaria, Lupinus, Fragaria, Galium, Lathyrus, Lithospermum* and *Berberis repens* and *Sedum Douglasii.*

* The term *forb* (pl. = *forbs*) is used to denote herbs other than grasses.

GRASSLAND FORMATION

V. Prairie: *Stipa-Bouteloua* Formation

5. Palouse Prairie (Bunchgrass): *Agropyron-Festuca* association.

The bunchgrass prairie was best developed in the Palouse region in Latah, Nez Percé and Lewis counties on the western edge of the central part of the state. It also occurred in the southern and eastern parts of the state below the coniferous forest and above the sagebrush. There was 10 to 20 inches of rainfall, most of it falling between September and April. The dominant perennial grasses formed bunches or clumps rather than a continuous sod.

Bunchgrass has nearly disappeared from the state, especially in the southern and eastern parts. It is difficult to determine its original boundaries due to its almost complete destruction, indeed, some of the "earliest" settlers maintain that it never existed in many places. A study of relic areas, steep slopes inaccessable to stock, railroad-rights-of-way, and protected enclosures, however, indicates that it extended a considerable distance into what is now sagebrush. The bunchgrass area has decreased more than 50% in Idaho and the density 40%. Changes in the plant cover are indicated by the following table (*16*):

Composition

	Range	
	Virgin	Present
Perennial grasses	76	4
Annual grasses	12	51
Forbs	10	35
Shrubs	2	10
Total	100	100

The original cover consisted of bluebunch wheatgrass (*Agropyron spicatum*), Sandberg bluegrass (Poa *secunda*), Idaho fescue (*Festuca idahoensis*), giant wild rye (*Elymus condensatus*), June grass (*Koeleria cristata*), needlegrass (*Stipa comata*), *Draba verna*, and species in the following genera: *Balsamorrhiza*, *Agoseris*, *Delphinium*, *Astragalus*, *Brodiaea*, *Lupinus*, *Cirsium*, *Geranium* and several species of umbellifers.

Due to over-stocking changes in these types have occurred. The bunchgrasses have mostly disappeared and many annual grasses, forbs and shrubs have replaced them. The most important are cheatgrass (*Bromus tectorum*), filaree (*Erodium cicutarium*), foxtail (*Hordeum jubatum*), Russian thistle (*Salsola pestifer*), tumbling mustard (*Sisymbrium altissimum*), *Polygonum aviculare*, *Lepidium perfoliatum*, and a number of poisonous plants including death camas (*Zygadenus paniculatus*), lupines (*Lupinus* spp.), and larkspurs (*Delphinium* spp.), have become more numerous. Sagebrush (*Artemesia tridentata*) and rabbitbrush (*Chrysothamnus nauseous*) have invaded and make up a considerable proportion of the vegetation, especially in the southern part.

WOODLAND CLIMAX

VI. Woodland: *Pinus-Juniperus* Formation

6. Pinon-Juniper Woodland: *Pinus-Juniperus* association.

This southwestern association reaches into the southern part of Idaho and is found mainly in Owyhee, Twin Falls and Cassia counties and in scattered locations in other counties. It is found on rocky slopes at elevations above sagebrush. The small shrubby trees were originally wide spaced and often appeared as though planted by man. The principal trees are Rocky Mountain red cedar (*Juniperus scopulorum*), Utah juniper (*J. utahensis*), and singleleaf pine (*Pinus monophylla*). *Pinus monophylla* occurs only in the southeastern part. No oak has been reported in the association or anywhere in Idaho. Originally there was a thin cover of vegetation between the scattered trees, but this has largely disappeared due to grazing. There has been an accompanying increase in the density of the trees. The grazing capacity has decreased more than 50 per cent (*16*).

SHRUB CLIMAX

VII. Sagebrush. *Artemesia-Atriplex* Formation

7. Great Basin sagebrush: Artemesia association.

Sagebrush covers most of the southern part of Idaho on the Snake River plains and occupies more than half of the area of the state. The precipitation is from 8 to 15 inches. The evaporation rates are high and less than 4 inches of rain falls during the growing season. Sagebrush is usually found in level places on deep soils free from alkali. Its original range was at elevations below the coniferous forest and bunchgrass.

In its original condition sagebrush (*Artemesia tridentata*), the principal dominant, grew to be a shrub up to 7 feet high and several feet apart. In between there were many grasses and forbs including wheatgrass (*Agropyron spicatum*), needlesgrasses (*Stipa* spp.), wild ryes (*Elymus* spp.), *Astragalus* spp., Indian ricegrass (*Oryzoides hymenoides*), yarrow (*Achillea millefolium*), *Chaenactis Douglasii*, balsamroots (*Balsamorrhiza* spp.), bitterbrush (*Purshia tridentata*), rabbitbrush (*Chrysothamnus nauseous*), and bud sage (*Artemesia spinescens*). It supplied many wild animals with forage.

Sagebrush stretches for hundreds of miles apparently with nothing but a continuity of dull gray sagebrush. There are now few plants growing in between the shrubs except in the spring when there may be a heavy growth of cheatgrass and a few ephemerals. Yet this area supplies forage for thousands of sheep and cattle on spring-fall range. It also supports countless numbers of gophers and rabbits which are said to have increased since their natural enemies have been greatly reduced. Nearly 9 acres are required to furnish forage for one cow for one month, where originally less than 3 were required (*16*).

Sagebrush has spread in Idaho and now occupies most of the original bunchgrass area. Some of it is irrigated, but most of it remains in the public domain and is used as open range.

The vegetation has been altered by the activities of man. There has been overgrazing for many years (*16*) and frequent range fires, many started by ranchers to burn off the sagebrush to cause what appears to be an increased growth of cheatgrass the following year. The sagebrush is much smaller and closer together and most of the original forbs and grasses have disappeared. Sagebrush is deep rooted and if the grasses and forbs are killed water will penetrate to the lower part of the soil. Restoration of the grass and forbus which have many shallow roots cuts off this supply of water and causes much of the sagebrush to die. In the bunchgrass area protection of the range would eventually result in the destruction of the sagebrush due to desiccation and the gradual replacement with bunchgrass. Some experiments have indicated that removal of the sagebrush by controlled burning followed by reseeding with grasses and protection from grazing tends to restore the grasses and forbs more quickly than natural succession.

The most abundant plant, in addition to sagebrush, is cheatgrass (*Bromus tectorum*), an European invader. In favorable years it may fill the spaces between the sagebrush. It provides most of the forage in spring and fall for sheep in southern Idaho. Cheatgrass matures quickly in the spring and after the long awns on the "seeds" develop it is unsuitable as forage. In summer the cheatgrass turns a reddish brown. It grows close together and is dry during the hot dry summers and frequently causes the spread of disastrous range fires. Other plants found in this type are larkspurs (*Delphinium* spp.), lupines (*Lupinus* spp.), death camas (*Zygadenus paniculatus*), onions (Allium spp.), filaree (*Erodium cicutarium*), tumble mustard (*Sisymbrium altissimum*), *Polygonum aviculare*, and *Hordeum jubatum*.

The salt desert shrub association also occurs in southern Idaho on alkaline soils. The dominant is shadscale (*Atriplex confertifolia*). Other shrubs are bud sage (*Artemesia spinescens*), rabbitbrushes (*Chrysothamnus* spp.), and winterfat (*Eurotia lanata*). The important grasses included Indian ricegrass (*Oryzopsis hymenoides*), squirreltail (*Sitanion hystrix*), alkali saccaton (*Sporobolus airoides*) and wild ryes (*Elymus* spp.). The area of this type has not been altered much, but most of the original forage plants have disappeared. Little rabbitbrush (*Chrysothamnus stenophyllus*), shad scale (*Atriplex confertifolia*) and snakeweed (*Gutierrezia Serothrae*) have spread and now occupy most of the type. Some areas unsuited for grazing are still in a virgin condition.

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